Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **23**, 625–641 (1998)

AEOLIAN DEPOSITS ON A SCOTTISH MOUNTAIN SUMMIT: CHARACTERISTICS, PROVENANCE, HISTORY AND SIGNIFICANCE

COLIN K. BALLANTYNE*
School of Geography and Geosciences, University of St Andrews, Fife, KY16 9ST, UK

Received 19 March 1997; Revised 20 September 1997; Accepted 28 October 1997

ABSTRACT

The summit plateau of The Storr (719 m) in northern Skye is mantled by a sheet of aeolian sediment up to 2·9 m thick, covering an area of 33 000 m^2 with a volume of 41 000 m^3. The deposits are of massive, poorly sorted sand with significant components of silt and fine gravel, and contain clasts up to 109 mm in length. The thickness and coarseness of the deposits decline westwards and northwards away from the highest cliffs, implying that the sediment comprises particles dislodged from rockwalls and blown upwards in an accelerating vertical or near-vertical airflow, settling through a lower-velocity flow onto the plateau surface where they are trapped by vegetation. Radiocarbon dating of soils buried under and within the deposits suggests that accumulation began after 7·2–6·9 calendar ka BP but before 5·6–5·3 calendar ka BP, and was probably initiated by exposure of the present rockwall by a massive landslide at *c*. 6·5±0·5 calendar ka BP. Pollen analyses of buried organic horizons suggest that a vegetation mat dominated by grasses and sedges was present throughout the period of sediment deposition. Sediment accumulation over much of the plateau averaged 10–20 mm per century throughout the late Holocene, but reached *c*. 60 mm per century in the area of the thickest deposits. the volume of the deposits implies the removal of 420–480 mm of rock (averaged over the face) during the late Holocene, and suggests that small-scale granular disaggregation and release of small clasts constitute a major component of rockwall retreat under present conditions. The origin of the Storr deposits suggests that plateau-top aeolian sediments on other Scottish mountains accumulated in a similar way, but have been eroded and redeposited on lee slopes following breakage of vegetation cover.

KEY WORDS: aeolian sediments; sand sheets; Holocene; rockwall retreat; Scotland

INTRODUCTION

In present-day cold environments, sand sheets of aeolian or niveo-aeolian origin are mainly associated with high-latitude lowlands, for example in arctic Canada and Alaska (Péwé, 1975; Nickling, 1978; Koster, 1988; French, 1996). Sites of active aeolian accumulation in such environments frequently reflect a nearby source of fine sediment, usually an unvegetated floodplain or sandur (Pissart *et al*., 1977; Good and Bryant, 1985; McKenna-Neuman and Gilbert, 1986) or recently deglaciated terrain (Riezebos *et al*., 1986). Active periglacial sand sheets have also been recognized in some mid-latitude alpine or plateau periglacial environments (e.g. Thorn and Darmody, 1980, 1985; Francou *et al*., 1990), though these tend to be less extensive than their arctic counterparts.

Accumulations of windblown sediment have also been reported on mountains in the Scottish Highlands, which currently experience a 'maritime periglacial' regime characterized by extreme wetness and very strong winds rather than severe cold and deep ground freezing (Ballantyne, 1987, 1991a; Ballantyne and Harris, 1994). Such deposits achieve their greatest extent and thickness on the Torridon Sandstone rocks of the NW Highlands (Peach *et al*., 1913; Godard, 1965; Ballantyne and Whittington, 1987; Ballantyne, 1993, 1995) but also occur on high ground underlain by other lithologies, including Devonian Sandstone on Orkney (Goodier and Ball, 1975), granite on Shetland and the Cairngorms (Ball and Goodier, 1974), Cambrian Quartzite in NW Scotland (Pye and Paine, 1983), Tertiary basalts on Mull (Birse, 1980), Moine Schists in the NW Highlands and Tertiary ultrabasic rocks on Rhum. High-level aeolian deposits on Scottish mountains generally take the form of

* Correspondence to: C. K. Ballantyne, School of Geography and Geosciences, University of St Andrews, Fife, KY16 9ST, UK
Contract/grant sponsor: British Geomorphological Research Group

CCC 0197-9337/97/070625–17 $17.50

vegetation-covered sand sheets, often less than 1·0–1·5 m thick but locally achieving depths of up to 4 m. They are typically massive and poorly sorted, and some appear to have a predominantly niveo-aeolian origin (Ballantyne and Whittington, 1987). Most high-level sand sheets in Scotland exhibit evidence of extensive recent erosion, being bounded by actively eroding scarps. The thickest deposits often lie downwind from extensive deflation surfaces that commonly support widely spaced remnant outliers of aeolian deposits. The latter indicate that a vegetated cover of windblown sediment was at one time much more widespread on exposed cols and plateaux, but has been stripped and redeposited on adjacent lee slopes (Ball and Goodier, 1974; Goodier and Ball, 1975; Pye and Paine, 1983; Ballantyne, 1995).

The history of aeolian accumulation on the Torridon Sandstone mountain of An Teallach in NW Scotland has been reconstructed by Ballantyne and Whittington (1987). At this site, deposition of windblown sands began in the early Holocene following the establishment of a stable vegetation cover. Ballantyne and Whittington inferred that a vegetated cover of sand up to 2·2 m thick eventually covered much of the exposed northern plateau of the mountain. This prolonged period of accumulation appears to have been terminated by the breaking of the vegetation cover on the plateau, leading to widespread erosion of sand from exposed locations and its redeposition on neighbouring lee slopes. Ballantyne and Whittington suggested that the break-up of vegetation cover on An Teallach and elsewhere may reflect increased storminess during the 'Little Ice Age' of the 17th and 18th centuries AD, or possibly overgrazing of grassland vegetation following the introduction of sheep to high ground, but the cause of erosion remains uncertain (Ballantyne, 1991b). A further uncertainty concerns the source of the sand deposits at this and other upland sites prior to reworking. The mineralogical composition of aeolian deposits at all upland sites hitherto investigated is identical to that of the underlying lithology, and appears to reflect entrainment of grains released by granular disaggregation of exposed bedrock and clast surfaces, rather than reworking of till or other drift deposits, but at some sites the potential source area of exposed rock surfaces on upland plateaux prior to recent reworking appears inadequate to account for the observed volume of aeolian sediment.

An opportunity to determine the characteristics and origin of unreworked high-level aeolian deposits is provided by the discovery of a blanket of windblown sediment on the summit plateau of The Storr (719 m) in northern Skye (Ballantyne, 1991c; Figure 1). This site differs from those previously investigated in Scotland in that it supports a virtually intact cover of aeolian sediment that has not experienced the extensive erosion and reworking evident elsewhere. Moreover, unlike most other upland aeolian deposits, those on The Storr occupy the very highest ground and hence cannot have been derived from deflation of sediment from exposed plateaux upwind. The research reported here focuses (1) on establishing the distribution, thickness and sedimentological characteristics of the windblown sediments on the summit of The Storr, (2) on reconstructing the history of aeolian accumulation through radiocarbon dating and pollen analysis of buried and intercalated organic horizons, and (3) on determining the origin and provenance of these deposits. The wider significance of this site for understanding the evolution of high-level aeolian deposits is then assessed.

THE STORR, TROTTERNISH, ISLE OF SKYE

The Storr (719 m; 57°32′N, 6°12′W; Figure 1) is the highest point on the Trotternish Escarpment in northern Skye. The escarpment is underlain by westward-dipping Tertiary plateau lavas, primarily olivine basalts (Anderson and Dunham, 1966). The western slopes of The Storr are moderate, with few rock outcrops, and support a complete vegetation cover with a widespread cover of peat below *c*. 600 m (Birks, 1973). Immediately east of the summit, foundering of the relatively incompetent sedimentary rocks that underlie the lavas has resulted in successive rotational landslides, forming one of the most extensive areas of landslip in Britain (Anderson and Dunham, 1966; Ballantyne, 1991d,e). During the maximum of the last (Late Devensian) ice-sheet glaciation, the higher parts of The Storr remained above the ice (Ballantyne, 1990, 1994), but adjacent areas of pre-glacial landslip were strongly ice-moulded. After deglaciation the entire SE face of the mountain collapsed to produce a great hollow, Coire Faoin, which is bounded to the NW by basalt cliffs up to 170 m high that meet the summit plateau at a sharp crest (Figure 2). Cosmogenic ^{36}Cl exposure dating of two postglacial landslide blocks indicates that failure and exposure of the present cliff face occurred at 6·5±0·5 calendar ka BP (Ballantyne *et al*., 1998). The summit area of The Storr above 570 m supports several active periglacial forms,

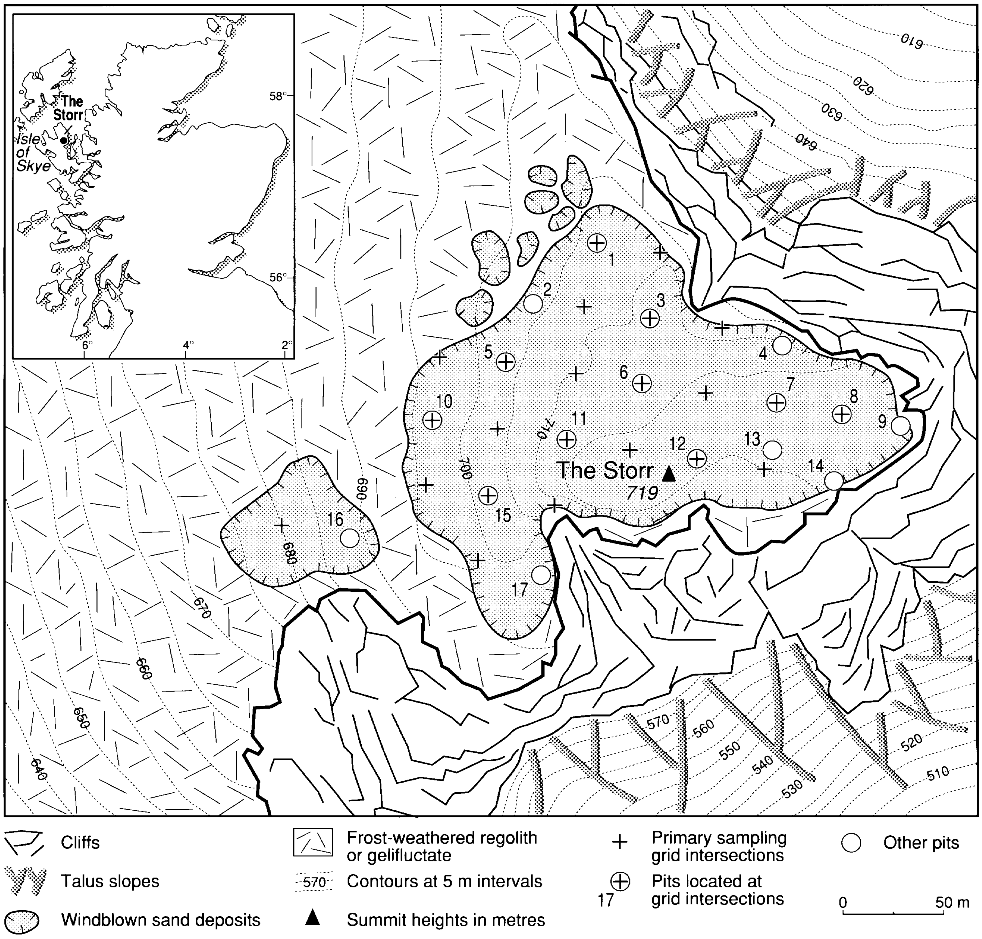


Figure 1. Distribution of windblown sediment >20 cm thick on the summit plateau of The Storr, Isle of Skye, Scotland. Open circles mark the location of sampling pits excavated through the deposit, and crosses mark sampling grid intersections

including solifluction lobes, ploughing boulders and miniature sorted nets, but for the most part consists of vegetation-covered gelifluctate and frost regolith, the latter being completely buried by windblown sediment on ground above 695–705 m (Ballantyne, 1991c). Present climate is dominated by high precipitation and strong winds rather than extreme temperatures. The estimated precipitation for the summit of The Storr is *c*. 2400 mm a^{-1} (Meteorological Office, 1977), and records for nearby areas suggest that mean annual air temperature on the summit is *c*. +4°C (Birks, 1973). Comparison with snow-lie records for An Teallach, 70 km to the NW, suggests that the summit of The Storr experiences an average of 50–70 days of >90 per cent snowcover per year (Ballantyne and Harris, 1994). The vegetation cover on the highest ground is characterized by Cariceto-Rhacomitretum lanuginosi heath, with grasses (particularly *Festuca ovina–Luzula spicata* communities) and sedges predominant on the aeolian deposits at the summit of the mountain (Birks, 1973).

FIELD METHODS

The aeolian deposits on the summit plateau of The Storr were mapped at a scale of 1:2500 and a primary grid of 29 points was surveyed across the surface of the deposits at 30 m intervals (Figure 1). Seventeen pits ranging in depth from 0·46 m to 2·29 m were dug through the deposits to the underlying frost-weathered regolith at or near alternating grid points, and the depth of the deposits at an additional 85 regularly spaced points on the survey grid was determined by augering. All soil pits were logged, and samples withdrawn for particle-size analyses,

Figure 2. Basalt cliff at the head of the Storr landslide, adjacent to the summit of the mountain. The vegetated area (top left) represents the edge of the windblown sediments, which are locally separated from the clifftop by a rock pavement up to 15 m wide

Figure 3. Crescentic deflation scar at the southwest margin of the aeolian deposit. Frost-weathered boulders emerge at the surface as the deposit thins downslope. The graduations on the survey pole are at 0·5 m intervals

with intensive sampling at two deep sites (7 and 13 in Figure 1) to establish if the deposits exhibit granulometric variation with depth. In addition, four samples were collected from organic horizons beneath or within the deposits for pollen analysis and radiocarbon dating.

CHARACTERISTICS OF THE AEOLIAN DEPOSITS

General description

The aeolian deposits on The Storr form a continuous, gently undulating sheet that mantles the highest part of the plateau, flanked to the west and northwest by a number of small outlying accumulations. Collectively, the deposits have a total area of *c*. 33 000 m^2, and apart from an outlier of sediment west of the main accumulation,

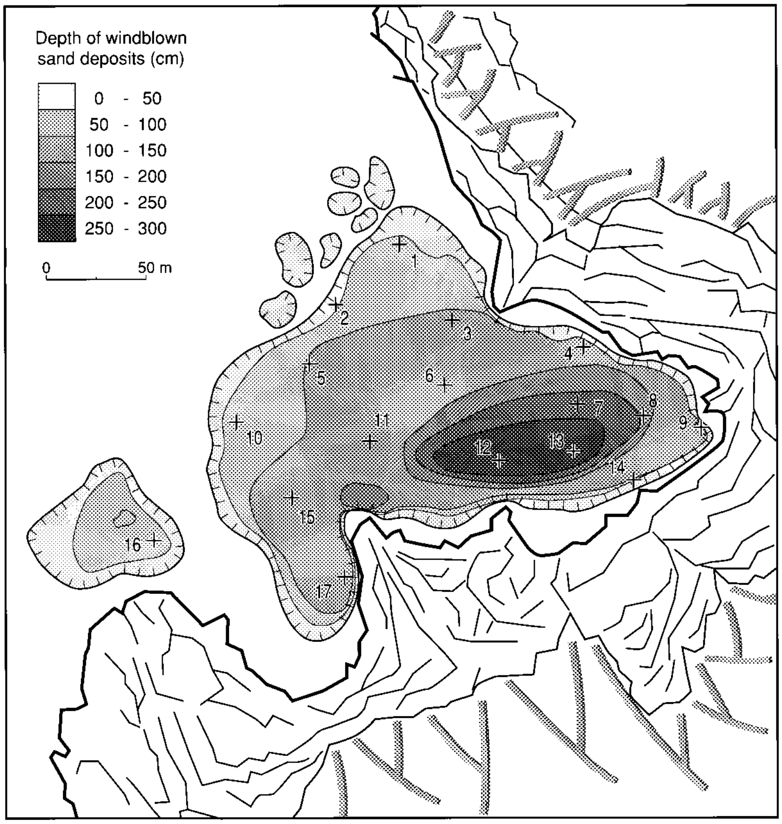


Figure 4. Isopach map of the thickness of windblown sediments on the Storr plateau

occupy the very highest part of the mountain between 695 m and the summit at 719 m (Figure 1). Vegetation cover is continuous, except where a few low cuspate scarps border the deposit to the west (Figure 3), and for a more extensive area of deflation east of the summit, adjacent to pit 13 (Figure 1). The main plateau deposit is bordered to the southeast by steep (*c*. 70°) basalt cliffs that plunge 130–170 m down to vegetated talus slopes below (Figure 2), and to the northeast by a gentler scarp up to 30 m high. The sediment cover only locally extends to the crest of the cliffs, however, being for the most part separated from it by a zone of bedrock 2–15 m wide. To the north and northwest the thinning margin of the sand is marked by the protrusion of large boulders through the aeolian cover, which gradually gives way to partly vegetated frost debris. The western boundary of the deposit is marked by a change from the predominantly grassland flora of the aeolian deposits to the heathland flora of the surrounding slopes, by flushes marking the emergence of springs draining the aeolian sediments, and locally by shallow eroded scarps. These scarps suggest that the deposit was once slightly more extensive. Unlike other sites in Scotland that support high-level aeolian sands, however, evidence for widespread stripping of aeolian deposits (e.g. outliers of sediment surrounded by extensive deflation surfaces) is absent on The Storr. Apart from the minor erosion scars described above (Figure 3) the deposit is essentially intact.

Depth and volume

Depth data collected at the 17 excavated pits and 85 augered points on the survey grid permitted construction of an isopach map summarizing the thickness of the aeolian sediments (Figure 4). This shows that the main part of the deposit thickens rapidly away from its margins to depths exceeding 0·5–1·0 m, and that the characteristic depth of the western part lies between 0·5 m and 1·5 m. The most interesting feature, however, is the thickening of aeolian sediment in the eastern part of its outcrop, where it achieves depths exceeding 2·5 m, with a maximum thickness of 2·9 m being detected in pit 13 (Figure 5). This area of deep sediment cover occupies a

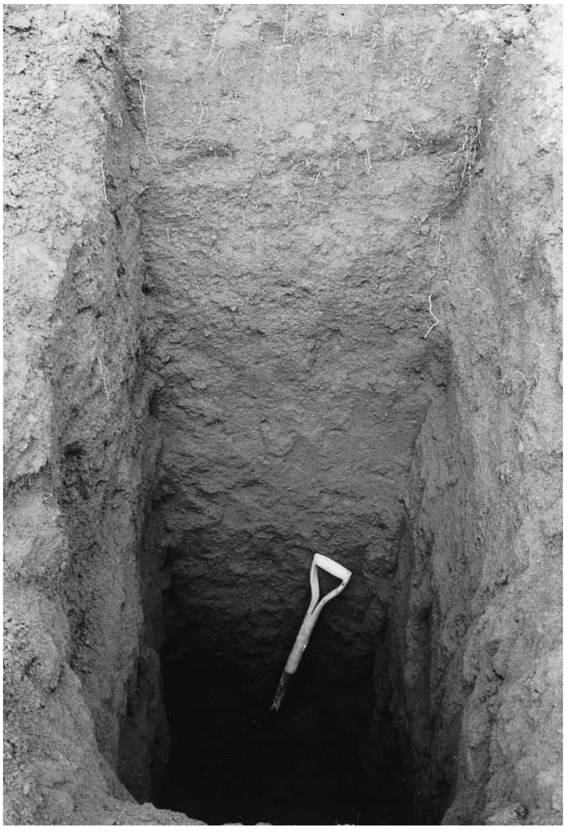


Figure 5. Pit 13, located 65 m ENE of the summit of The Storr. The spade is one metre long. Windblown sediments reach a thickness of 2·9 m at this site

50 m wide band east of the summit and is markedly asymmetrical in form, thinning abruptly to the south but more gently to the north. The average thickness of aeolian deposits indicated by the depth data is 1·25 m, implying that a total volume of 41 000 m^3 of windblown sediment overlies bedrock and frost-weathered regolith on the summit plateau of The Storr.

Sedimentology

In all 17 excavated pits, the bulk of the sediment accumulation appears as a massive, structureless, poorly sorted reddish to reddish brown sand (Figure 5) with a significant proportion of silt and, in most pits, occasional angular flakes of basalt up to 6 cm long and very occasional larger flakes up to 11 cm long. The uppermost 15–29 cm of the deposit in all sites consists of a dark brown modern soil, but rootlets were evident at all depths in all sections. Pits near the margins of the deposit were generally dry, but nearer the centre the water table lay up to a metre above the underlying frost debris. Many pits exhibited poorly defined banding due to colour changes, principally 7–16 cm thick bands of dark brown sediment similar in colour and texture to the modern soil, though a few contained mottled orange iron-rich horizons. Four pits (6, 9, 13 and 15) contained very dark brown to black organic-rich horizons that were sampled for pollen analysis and radiocarbon dating. Changes in texture were only occasionally apparent, though pits 4, 5 and 15 contained thin layers of coarse sand that may represent localized reworking of aeolian sediment by surface wash.

A total of 67 samples, each 200–300 g in weight, were collected for particle-size analysis. These comprised two to four samples at most pits, samples being collected from near the base of each pit and at a depth of 20 cm, with up to two intermediate samples, depending on pit depth. In addition, samples at 20 cm vertical intervals were collected at pits 7 and 13 to establish variation in particle size with depth. All samples were analysed by wet sieving at half-phi intervals through nests of sieves over the range -3ϕ (8 mm) down to 4ϕ (63 μm) and residual sediments finer than 63 μm were analysed by Coulter Counter. The results were analysed by plotting

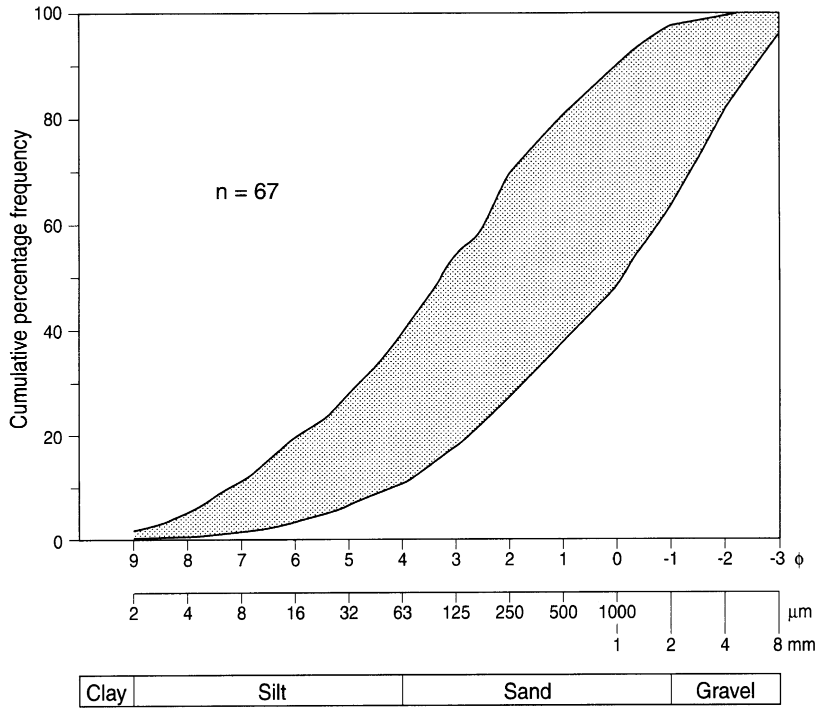


Figure 6. Particle-size envelope for 67 samples of windblown sediment from the summit plateau of The Storr

the cumulative frequency distributions for all samples, first for all particle sizes and secondly for particles finer than 2 mm, then calculating summary statistics based on graphic measures (McManus, 1988).

Figure 6 depicts an envelope curve delimiting the cumulative percentage frequency of particle sizes for all samples. Clay (<2 µm) was negligible in most samples. Total silt content (2–63 µm) ranged from 11 per cent to 40 per cent by weight, with a mean of 25 per cent; sand (63–2000 µm) from 32 per cent to 64 per cent with a mean of 50 per cent; and fine gravel (2–8 mm) from 4 per cent to 36 per cent, with a mean of 24 per cent. For the full range of particle sizes, the average graphic mean is 1·50ϕ (354 µm), the inclusive graphic standard deviation ranges from 2·59ϕ to 3·19ϕ, indicating that all samples are very poorly sorted, and inclusive graphic skewness ranges from –0·02 to –0·48, indicating a range from near-symmetrical to very negative skew. For particle sizes finer than 2 mm, the equivalent figures are an average graphic mean of 2·61ϕ (164 µm), an inclusive graphic skewness range of 2·26–2.67ϕ, again indicating very poor sorting, and a skewness range of +0·03 to –0·51, again indicating near-symmetrical to very negative skew (McManus, 1988). In sum, the sediments are overall very poorly sorted and extremely variable in granulometry (Figure 6). Most samples are dominated by sand-sized sediment, but all contain appreciable components of both silt and fine gravel.

Vertical variations in particle size

To establish the range and possible trend of particle-size variations with depth, samples were collected at 20 cm vertical intervals from pits 7 and 13, and analysed in terms of the graphic mean for particles finer than 2 mm and the percentage by weight coarser than 2 mm. The results (Figure 7) reveal no systematic trend with increasing depth. At pit 7, the average mean particle size <2 mm is 2·53ϕ, with a standard error of 0·14ϕ; at pit 13 the equivalent parameters are 2·59ϕ and 0·05ϕ. The average percentage by weight coarser than 2 mm for the pit 7 samples is 24·8 per cent, with a standard error of 1·4 per cent, and that at pit 13 is 27·0 per cent, with a standard error of 1·1 per cent. These results indicate limited variation in particle-size distribution during the period of deposition, suggesting little change in depositional processes. Moreover, the consistency of these parameters at these two sites suggests that much of the overall variation in particle size (Figure 6) may reflect horizontal variations across the deposit.

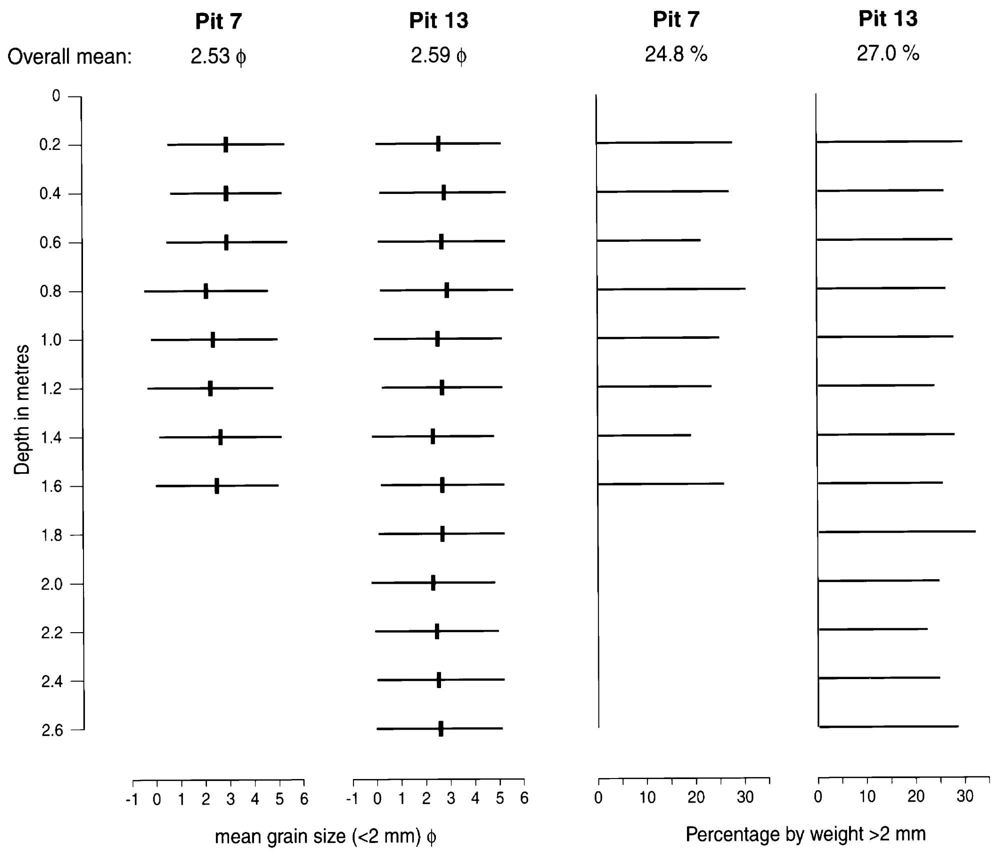


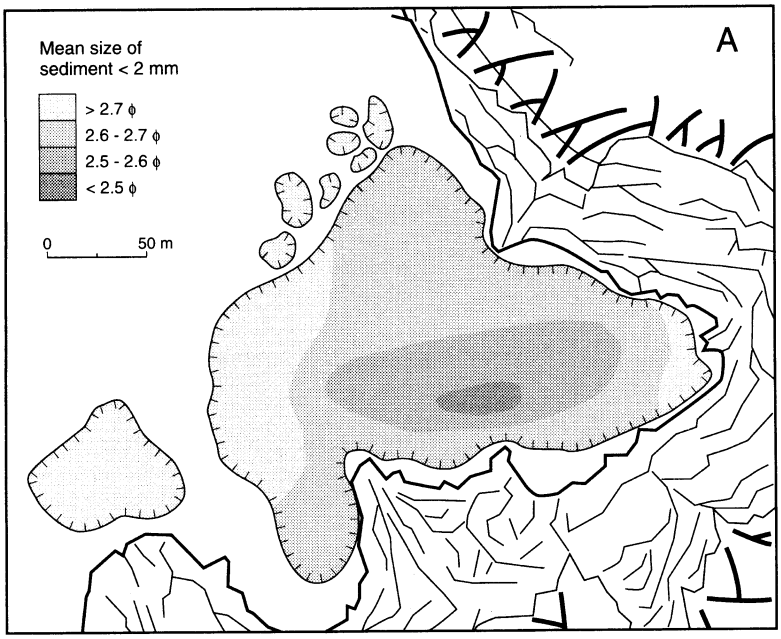
Figure 7. Variations in particle-size parameters with depth at pits 7 and 13. The two columns on the left give the values of the graphic mean (vertical lines) and inclusive graphic standard deviation (horizontal lines) for particle-size distributions finer than 2 mm (–1ϕ). The two columns on the right show the percentage by weight coarser than 2 mm

Horizontal variations in particle size

Variations in particle size across the deposit were assessed by averaging the results of particle-size analyses for all samples at each site, irrespective of sampling depth. Horizontal variations in grain size were investigated in terms of both averaged graphic means for grains <2 mm and the averaged percentage by weight >2 mm. The results were then used to interpolate isometric lines across the deposit (Figure 8). In interpreting these maps, however, it must be borne in mind that they reflect only averaged parameters, and that a few individual samples are inconsistent with the general trends. The pattern of averaged graphic means for grains finer than 2 mm (Figure 8A) shows considerable similarity to that of sediment thickness (Figure 5). The thickest sediments (>1·5 m) generally correspond to sites where the averaged mean size of particles finer than 2 mm is coarser than 2·6ϕ (*c.* 160 μm), and mean particle size tends to diminish with distance away from the cliffs that border the southern side of the deposit. The pattern exhibited by the averaged percentage by weight of particles >2 mm is less regular (Figure 8B) suggesting that this value tends to be high (>20 per cent) in the central and eastern parts of the deposit, but to diminish to <15 per cent in the western part, though this conclusion hinges on a small number of samples from the western edges of the deposit.

RADIOCARBON DATING AND POLLEN ANALYSIS

Samples for radiocarbon dating and pollen analysis were collected from organic-rich horizons at the base of or intercalated with aeolian sediments at four sites. At no site was more than one organic-rich horizon evident. Sample Storr 1 (pit 9) represents the uppermost organic horizon of an alpine brown soil developed in frost-



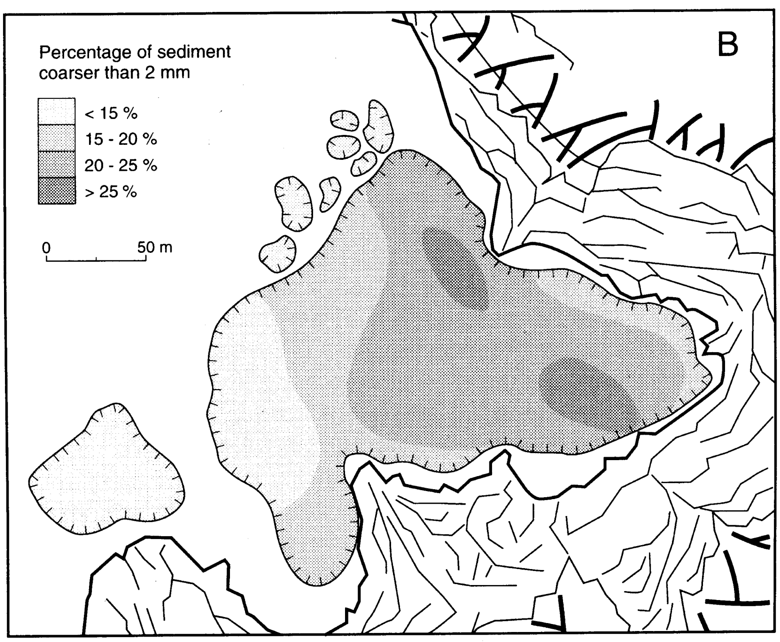


Figure 8. Isolines showing variations in averaged particle-size parameters across the deposit. (A) Variations in the averaged graphic mean for particles <2 mm. (B) Variations in the average percentage by weight of sediment >2 mm

weathered regolith that underlies 102 cm of aeolian sediment at the edge of the plateau. Storr 2 (pit 6) represents the uppermost organic horizon of a mature, mottled gley soil developed in 18 cm of basal sand and overlain by 120 cm of windblown sediment. Storr 3 (pit 13) was sampled from a thin organic-rich horizon 55 cm from the base of the aeolian sequence and overlain by 235 cm of windblown deposits. Storr 4 (pit 15) was obtained from a 15 mm thick organic-rich layer developed on 54 cm of aeolian deposits and overlain by a further 61 cm of windblown sediments. All samples were pretreated and oxidized to CO_2 at the NERC Radiocarbon Laboratory,

Table I. AMS radiocarbon dates from organic horizons within the Storr summit sand sheet

Sample no.	Pit no.	Pit depth (cm)	Sample depth (cm)	Laboratory code	Radiocarbon age (^{14}C years BP)	δ^{13}C (‰)	Calibrated age* (calendar years BP) range	P
Storr 1	9	102	102	AA-13301	6210±60	–25·3	7230–6970 6960–6940	(0·97) (0·03)
Storr 2	6	138	120	AA-13302	4810±65	–25·9	5650–5450 5410–5330	(0·83) (0·17)
Storr 3	13	290	235	AA-13303	3665±55	–26·2	4150–4100 3190–3830 3790–3780	(0·07) (0·92) (0·01)
Storr 4	15	115	61	AA-13304	3230±60	–26·2	3630–3620 3570–3320 3280–3270	(0·02) (0·97) (0·01)

* Calibrated calendar ages were calculated using the CALIB rev 3.0 programme of Stuiver and Reimer (1993) and the calibration data of Stuiver and Becker (1993). Due to short-term variations in atmospheric ^{14}C concentration, some radiocarbon ages convert to more than one calendar age span. The probability (*p*) values provide an estimate of the relative importance of each calendar age range option within 95 per cent (±2σ) confidence limits

Table II. Average rates of sediment accretion based on calibrated radiocarbon dates

Sample no.	Pit no.	Pit depth (cm)	Depth range (cm)	Age range (cal. years BP)	Average rate of sediment accretion (mm a^{-1})
Storr 1	9	102	102–0	≤7230–6940 to present	≥0·14–0·15
Storr 2	6	138	120–0 138–120	5650–5330 to present ≤7230–6940 to 5650–5330	0·21–0·22 ≥0·10–0·14
Storr 3	13	290	235–0 290–235	4150–3780 to present ≤7230–6940 to 4150–3780	0·57–0·62 ≥0·16–0·20
Storr 4	15	115	61–0 115–61	3630–3270 to present ≤7230–6940 to 3630–3270	0·17–0·19 ≥0·14–0·16

and aliquots of the prepared gas were forwarded for accelerator-beam measurement at the University of Arizona NSF-AMS facility. The radiocarbon ages (Table I) were translated into calendar year ranges using the CALIB rev 3.0 programme of Stuiver and Reimer (1993) and the calibration data of Stuiver and Becker (1993).

The date obtained for sample Storr 1, an organic soil underlying the aeolian sequence, suggests that sediment accumulation commenced at this site after 6330–6090 a BP (7230–6940 calendar a BP). The younger dates for samples Storr 2–4 (all of which occur *within* the sand deposit, and are thus stratigraphically higher) are consistent with this estimate, and suggest progressive accumulation of the deposit during the late Holocene. If the Storr 1 date is assumed for the onset of sediment accumulation across the plateau, it is possible to calculate approximate minimum or average rates of sediment accretion before and after the formation of the dated organic horizons at the other three sites (Table II). These calculations suggest that, over most of the deposit, sediment has accumulated at an average rage of 0·10–0·22 mm a^{-1} (10–22 mm per century), though accumulation was much more rapid over the last four millennia in the area of thick sand deposits around pit 13 (0·57–0·62 mm a^{-1}, or approximately 60 mm per century). The data also suggest slight (pits 6 and 15) or marked (pit 13) increases in the rate of sediment accumulation above the dated organic horizons compared with the estimated rates for below these horizons, but this difference could also reflect differences in the age of the onset of sediment accumulation at these sites.

Pollen assemblages were analysed for all of the dated organic horizons to determine the nature of vegetation cover during the period of sediment accumulation. Single samples were counted for samples Storr 1 and Storr 4, two samples were analysed from the top and base of Storr 3, and ten samples at 15 mm vertical intervals were analysed from a monolith sample that spanned the buried soil in pit 6 (Storr 2); 300–500 grains were counted in each case. The results show a persistent dominance (45–70 per cent) of Poaceae in all samples, suggesting that

the grassland vegetation that presently dominates the summit area of The Storr remained largely unchanged during the period of sediment deposition. *Corylus avellana*-type pollen are also strongly represented throughout, but show a progressive decline from 32 per cent in the oldest sample to <15 per cent in Storr 3 and Storr 4, consistent with a general mid- to late-Holocene decline in this pollen taxon in cores from lowland sites in northern Skye (Vasari and Vasari, 1968; Birks and Williams, 1983; Lowe and Walker, 1991). Inblown grains of *Pinus sylvestris* are present in most samples and show no pattern through time, but the representation of *Alnus glutinosa* pollen increases progressively from zero in the oldest sample to 7 per cent in the youngest, possibly reflecting wetter conditions and the establishment of the alder carrs that presently follow stream courses on the low ground surrounding the mountain (cf. Vasari and Vasari, 1968). Another interesting trend is a progressive increase in *Potentilla*-type pollen from <1 per cent in the oldest sample to 3–6 per cent in Storr 3 and Storr 4. This trend may reflect human disturbance of vegetation on surrounding low ground (Birks and Williams, 1983), a hypothesis supported by an increase in charcoal concentration from $<0{\cdot}10\,cm^2\,cm^{-3}$ in the two oldest samples to $0{\cdot}83\,cm^2\,cm^{-3}$ in Storr 3 and $2{\cdot}43\,cm^2\,cm^{-3}$ in Storr 4.

In sum, the stratigraphic, radiocarbon and pollen evidence collectively suggests progressive accumulation of windblown sediment that commenced around or after 6·3–6·1 ka BP (7·2–6·9 calendar ka BP) but well before 4·9–4·7 ka BP (5·6–5·3 calendar ka BP) on an exposed plateau supporting, as at present, a dominantly grassland vegetation. There is no stratigraphic evidence for distruption of cover during this period, and the presence of rootlets at all depths in all sections suggests that sediment blown onto the plateau was trapped by the grassland vegetation, which was able to keep pace with sediment accumulation (cf. Ballantyne and Whittington, 1987). Over much of the plateau the average rate of sediment accumulation did not exceed $0{\cdot}25\,mm\,a^{-1}$, but reached *c*. $0{\cdot}6\,mm\,a^{-1}$ in the area of the thickest deposits on the southern part of the plateau above the highest cliffs. The pollen evidence suggests changes in vegetation cover on the surrounding low ground in the form of increased wetness and possibly the onset of anthropogenic disturbance sometime after *c*. 4·9–4·7 ka BP (*c*. 5·6–5·3 calendar ka BP); the latter inference is supported by a dramatic increase in charcoal counts, possibly associated with burning of vegetation for clearance. It is notable, however, that the evidence for human disturbance of vegetation on low ground clearly post-dates the onset of aeolian sedimentation on The Storr, suggesting that the two phenomena are unrelated.

ORIGIN AND TRANSPORT OF AEOLIAN SEDIMENTS

Sediment sources and transport paths

The plateau-top location of the windblown deposits on The Storr implies that these were derived either from the slopes west and northwest of the summit, or from the cliff faces bordering the summit on its southern and eastern sides. Although the former possibility is favoured by the predominance of westerly winds in northwest Scotland, it encounters several objections. First, the slopes west and northwest of the summit presently support a complete vegetation cover and a cover of blanket peat (Birks, 1993). This peat cover thickens downslope, reaching a depth of over one metre in streambank exposures one kilometre west of the summit. Although the age of the onset of peat growth on the slopes of The Storr is unknown, blanket peat growth at other hillslope sites in Scotland is known to have begun no later than *c*. 3·0 calendar ka BP, and at some sites has been dated to the very early Holocene (Tipping, 1995). As much of the windblown sediment on the summit of The Storr accumulated after 3·8–3·2 calendar ka BP (the age of sample Storr 3, which underlies 235 cm of aeolian deposits; Table I), it is probable that a protective peat cover developed west of the summit during or before the main period of aeolian accumulation, inhibiting entrainment of sediment by wind. Secondly, even if areas of unvegetated and peat-free terrain formerly existed west of the summit, the sediment would have to have been blown up of a gradient of *c*. 14° before stopping and accumulating on the exposed summit plateau, which seems implausible, particularly for flakes of basalt up to 11 cm in length. Finally, neither the spatial pattern of sediment thickness nor that of sediment texture supports a westerly origin. Had the sediment been derived from the west or northwest, then it might be expected to thin and fine eastwards and southeastwards across the summit plateau, but the reverse is true (Figures 4 and 8).

If a westerly source is excluded for the reasons indicated above, the only possible alternative is that the windblown sediments on The Storr were derived from the basalt cliffs that flank the summit plateau to the south

and east. This implies that particles loosened by weathering of the cliff face were blown *upwards* from the adjacent rockwalls and trapped by vegetation on the summit plateau. A similar process has been documented in two recent studies. Wilson (1989) has demonstrated that a thin sand sheet mantling part of the summit plateau of Muckish Mountain in Ireland must have formed through upblowing of grains derived from friable quartzite beds immediately below the crest of an adjacent cliff. Radiocarbon dating of buried organic horizons beneath the sand sheet on Muckish Mountain suggest that aeolian accumulation began at *c*. 5·3 ka BP, eventually reaching a maximum thickness of 80 cm. Wilson's conclusions regarding the rockwall source of plateau-top aeolian sediments are supported by Hétu (1992), who observed recent deposition of a drape of sediment up to 14 mm thick over snowcover at the crest of a rockwall in northern Gaspésie, Québec, and showed that this had been blown upwards from the adjacent cliff during a single storm. Trenching of the accumulated cliff-top sediments at the Gaspésie site and dating of buried wood fragments and organic layers indicated that cliff-top aeolian accumulation has been occurring intermittently for at least a millennium.

On Muckish Mountain, Wilson (1989) observed that windblown sand reaches its maximum thickness near the crest of the cliff, but thins to a few centimetres depth at a distance of 60 m from the cliff edge. Similarly, Hétu (1992) observed that the recent deposit of upblown sediment deposited on snowcover above the Gaspésie rockwall was concentrated in a belt 15–20 m wide adjacent to the crest of the cliff and diminished in thickness with distance from the crest. The spatial pattern of sediment depth on The Storr therefore resembles that observed in both previous accounts of cliff-top accumulation of upblown aeolian sediments, as the sediment mantle is thickest near the crest of the highest cliffs but thins westwards and northwards (Figure 4), suggesting that the 170 m high cliffs south of the plateau formed the main source of windblown sediment. The pattern of sediment thickness on The Storr is also strikingly similar to that described by Marsh and Marsh (1987), who observed 'berms' of windblown sand that had accumulated near the crest of coastal bluffs cut in sandstones and sandy glacial deposits.

The sedimentological characteristics of the Storr deposits exhibit some affinities with those of the Muckish Mountain and Gaspésie sediments. Samples from Muckish Mountain, like most of those from The Storr, are dominated by fine and medium sand. However, the Muckish Mountain samples are better sorted than those from The Storr, as the former contain much smaller quantities of silt (1–18 per cent, compared to 11–40 per cent) and fine gravel (1–14 per cent, compared to 4–36 per cent). The better sorting of the Muckish Mountain sediments could reflect the weathering characteristics of quartzite grains compared with particles derived from basalt. The Gaspésie cliff-top sediments resemble The Storr deposits in being very poorly sorted, but are generally coarser, with mean grain sizes ranging from $-1{\cdot}63\phi$ to $+2{\cdot}23\phi$, as opposed to $+0{\cdot}55\phi$ to $+2{\cdot}77\phi$ for the Storr sediments. The relative coarseness of the Gaspésie sediments may reflect sampling within the belt of thickest deposits immediately adjacent to the crest of the cliff, and the high windspeeds (up to 100 km h^{-1}) recorded during the storm that deposited these. Hétu (1992) also noted that the supranival cliff-top sediments deposited by the recent storm at the Gaspésie site included shale flakes up to 159 mm long, demonstrating that aeolian transport in such situations is capable of transporting the basalt flakes found in the Storr deposits, the largest of which was 109 mm long. In sum, the texture of the Storr sediments generally falls between those of the Muckish Mountain and Gaspésie deposits, and thus appears compatible with a rockwall origin, bearing in mind the differences in lithology and topography at the three sites.

A final point favouring derivation of the Storr deposits from the adjacent rockwall lies in the age of the oldest sediments. Radiocarbon dating (Table I) indicates that the deposits began to accumulate after 7·2–6·9 calendar ka BP but before 5·6–5·3 calendar ka BP. However, pollen analysis of organic layers within windblown deposits on An Teallach, 70 km NW of The Storr, indicates that accumulation of windblown sediment on that mountain began much earlier in the Holocene, following establishment of a stable vegetation cover (Ballantyne and Whittington, 1987). The delay in the onset of sediment accumulation on The Storr can be related to the age of the landslide that exposed the cliff faces east and south of the summit. In their reconstruction of the landslide, Anderson and Dunham (1966) estimated that prior to postglacial failure the scarp face lay *c*. 600 m east of its present position. Cosmogenic ^{36}Cl dating of landslide blocks by Ballantyne *et* . (1998) suggests that the landslide occurred within the period 7·0–5·9 calendar ka BP. It is probable, therefore, that the onset of aeolian accummulation on The Storr after 7·2–6·9 calendar ka BP and before 5·6–5·3 calendar ka BP relates to the timing of the landslide, which exposed the rockwall that now acts as a source of upblown

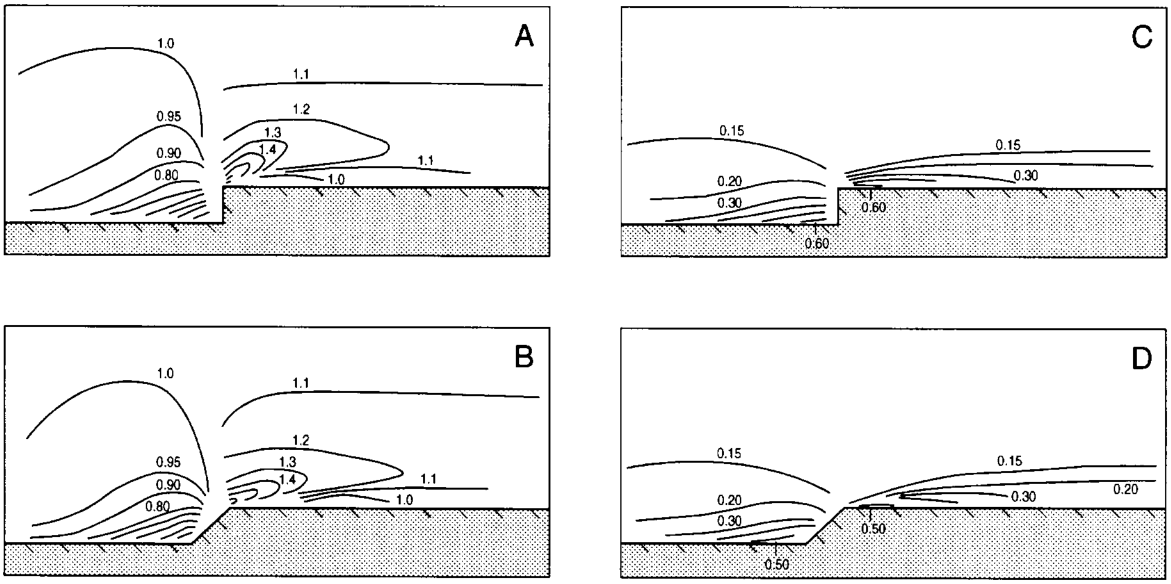


Figure 9. Results of wind-tunnel experiments by Bowen and Lindley (1977). (A and B) Isolines of equal amplification factor *Az* for the movement of wind across a vertical cliff (A) and 45° scarp (B). (C and D) Isolines of turbulence intensity associated with the movement of wind across the same slopes

sediment. Earlier aeolian sediments deposited near the pre-failure scarp crest would have been removed when the landslide occurred, allowing a new phase of aeolian accumulation to begin near the crest of the present rockwall. Owing to extensive break-up of the landslip block (Ballantyne, 1991e), however, no trace of pre-failure aeolian deposits has survived.

Theoretical considerations

In the case of particles dislodged from a cliff face, upward transport in suspension by a vertical or near-vertical airflow will occur when the velocity of the flow exceeds the settling velocity of the particles. Settling velocity in air increases non-linearly with particle size. Data from Cui *et al.* (1983) show that the settling velocity of natural quartz grains increases with intermediate axis diameter, reaching a value of *c.* 6 m s^{-1} (22 km h^{-1}) for quartz grains 2 mm in diameter. Extrapolation of these results by Pye and Tsoar (1990) suggests that the settling velocity of grains 8 mm in diameter is *c.* 9 m s^{-1} (33 km h^{-1}), and further graphical extrapolation suggests that for particles 100 mm in mean diameter (slightly larger than that of the largest flakes found in the Storr deposits) the settling velocity is unlikely to exceed 20 m s^{-1} (72 km h^{-1}), though Cui *et al.* (1983) caution against extrapolation of their findings for particles >2 mm.

The velocity and turbulence characteristics of winds meeting a steep cliff have been studied experimentally in a wind tunnel by Bowen and Lindley (1977). They expressed the airflow acceleration over the cliff as an amplification factor, *Az*, defined as the mean undisturbed flow velocity at a particular height above local ground level divided by the mean flow velocity at a similar height above flat ground upstream of the hill. They found that, at a point about one-third of the way up the face, *Az* reaches unity and increases rapidly towards the crest. In their model, *Az* reached a measured maximum of between 1·7 and 1·8 at a height of $0{\cdot}2H$ above a cliff height H (Figure 9A, B) though Bowen (cited in Marsh and Marsh, 1987) points out that for large slopes the amplification factor decreases with slope height, and is thus likely to be less than the model indicates. Nonetheless, the model suggests that the velocity of the airflow ascending the upper two-thirds of the face equals or exceeds the mean velocity of the wind over level ground upslope. As mean wind velocities >20 m s^{-1} (>72 km h^{-1}) are common during winter storms on Skye, and as *Az* exceeds unity over the upper two-thirds of the face, there is no theoretical difficulty in explaining the upward transport of sand, fine gravel and even small clasts from the cliff face on to the plateau above.

Bowen and Lindley (1977) also found that the crest marks a zone of flow separation, with a wake zone of relatively low mean velocity close to the plateau surface, above which accelerated flow velocities decline with distance from the crest (Figure 9A, B). As envisaged by Hétu (1992), this implies that particles falling out of suspension in the upper zone of high but declining velocity may settle through the underlying relatively low velocity zone and accumulate at the ground surface, where they are trapped by vegetation and where entrainment velocities are inadequate to initiate renewed movement. However, the wake region is also a zone of high turbulence intensity (defined by Bowen and Lindley (1977) in terms of the standard deviation of velocity divided by the mean), implying that particles may be supported in suspension by upward vortices for some distance in the lee of the crest (Figure 9C, D). This may explain why sediment thickness exceeds 0·5 m across most of the deposit, thinning rapidly at its edges. In sum, the distribution of sediment on the summit of The Storr and the pattern of sediment thickness (Figure 4) both appear consistent with the predictions of Bowen and Lindley's (1977) model, provided it is assumed that the dominant sediment-bearing winds were those arriving from sectors between south and east, and forced to accelerate up the highest cliffs. The pattern of sediment distribution also suggests that only a minor component of the deposit was derived from the much lower cliffs to the northeast of the plateau.

Implications for rockwall retreat

The total area of the rock cliff surrounding the Storr plateau to the south, east and northeast was calculated from enlarged 1:10 000 Ordnance Survey maps as planimetric area divided by (cos α) where α is the mean gradient of the rockwall measured from contours at 50 m horizontal intervals around the face. This yielded a range of 65 000–73 000 m^2 for rockwall area. The volume of the plateau-top sediment deposit is *c*. 41 000 m^3. Allowing 25 per cent for voids gives a total particle volume of *c*. 31 000 m^3, and division of this figure by the rockwall area estimates cited above yields *c*. 420–480 mm of rock removed from the cliff faces during the period of plateau-top sediment accumulation, assuming that the cliffs represent the sole source of windblown sediment. As the radiocarbon date for basal soil buried by the deposits (sample Storr 1, Table I) implies accumulation of the deposits after *c*. 7·2–6·9 calendar ka BP, this range translates into a minimum average rockwall retreat rate of 0·06–0·07 mm a^{-1}.

This figure is of interest for two reasons. First, it markedly exceeds estimates of recent rockwall retreat in Scotland and Wales based on the volume of accumulated coarse rockfall debris, which averages 0·015 mm a^{-1} (Ballantyne and Eckford, 1984; Ballantyne and Harris, 1994). If intermittent large-scale rockfalls are discounted, this suggests that granular disaggregation and release of small (<100 mm) particles from cliff faces may constitute the primary mode of rockwall retreat in upland Britain under present climatic conditions, particularly as the retreat rate figure of 0·06–0·07 mm a^{-1} is calculated on the basis of those particles that have travelled upwards from a weathering rockwall, and takes no account of those blown, falling or washed downslope (cf. Hétu. 1992). Secondly, it supports recent findings which suggest that granular disaggregation of cliff faces provides large quantities of fine sediment that accumulate in talus accumulations downslope. Salt and Ballantyne (1997) have demonstrated that relict talus deposits at Knockan in northern Scotland comprise *c*. 30 per cent fines (<2 mm) by weight, and Hinchliffe *et al*. (1998) have identified a similar component of fines in talus that has accumulated at the foot of the Trotternish Escarpment 2 km south of The Storr. In both cases, sedimentological and petrological analyses indicate that these fines were largely derived from the rockwall upslope, implying that *c*. 30 per cent of rockwall retreat since deglaciation has been due to small-scale weathering and detachment of grains rather than rockfall.

WIDER IMPLICATIONS

Most windblown sand sheets in Scottish mountains occur in lee locations, often downwind from deflation surfaces that are carpeted by a lag deposit of fine gravel but support remnant 'islands' of windblown deposits indicating a formerly much more extensive cover (e.g. Godard, 1965; Ball and Goodier, 1974; Goodier and Ball, 1975; Pye and Paine, 1983; Ballantyne and Whittington, 1987; Ballantyne, 1995). The Storr deposit is unusual in representing an essentially intact deposit of plateau-top windblown sediment. It has been argued above on the grounds of sediment distribution, depth and texture that the Storr deposits represent sediment dislodged from

adjacent cliffs during storms and blown upslope onto the plateau, where it accumulates in a wake zone of relatively low velocity airflow. This conclusion suggests that the former plateau-top sand cover on other Scottish mountains, such as An Teallach (Ballantyne and Whittington, 1987) and Beinn Mór Coigach (Ballantyne, 1995) may have accumulated in a similar manner, but have been eroded from exposed plateaux and cols following breakage of the vegetation mat, to be redeposited in sheltered locations. This interpretation is favoured by the stratigraphy of lee-slope deposits, which characteristically exhibit an upper unit of relatively unweathered sand (representing reworked plateau sediments) overlying a lower unit of more weathered sand that has accumulated progressively throughout most of the Holocene (Ballantyne and Whittington, 1987; Ballantyne, 1995). If this interpretation is correct, then it implies a two-stage origin for some, at least, of the aeolian sediment that mantles Scottish mountains: first, emplacement on exposed locations by winds blowing up rockwalls, and second, reworking of such deposits following disruption of the vegetation mat, and redeposition of sediment in sheltered locations. The timing and cause of vegetation destruction and consequent reworking of plateau-top aeolian sediment remain to be established, though the relative freshness of the upper sand unit in lee sites suggests that this occurred in late Holocene times.

CONCLUSIONS

1. The summit plateau of The Storr (719 m) in northern Skye is mantled by a sheet of aeolian sediments up to 2·9 m deep. These cover an area of *c*. 33 000 m^2 and have a total volume of *c*. 41 000 m^3. The area of thickest sediment forms a 50 m wide band above the highest (170 m) cliffs, thinning northwards and westwards.
2. The deposits are dominantly of massive, very poorly sorted sand with significant components of silt and fine gravel, and clasts up to 11 cm long. The sediments exhibit little change in granulometry with depth, but there is a general correspondence between the coarsest deposits and the area of thickest accumulation above the highest cliffs.
3. The distribution, depth variations and textural variations of the deposits are consistent with a southerly or southeasterly source, implying that the sediment comprises particles dislodged from surrounding rockwalls and blown upwards onto the plateau. Comparison with wind-tunnel modelling of airflow across escarpments indicates the feasibility of this process, and suggests that dislodged particles are blown upslope in an accelerating airflow but fall through a lower-velocity flow near the plateau surface.
4. Radiocarbon dating of soils buried under and within the deposits implies that the latter began to accumulate after *c*. 7·2–6·9 calendar ka BP, but before 5·6–5·3 calendar ka BP. The onset of accumulation probably reflects exposure of the present rockwall by a massive landslide at *c*. 6·5±0·5 calendar ka BP. Throughout the period of sediment accumulation the deposits supported a cover of dominantly grassland vegetation. Though there is some indication from pollen spectra and charcoal counts of human interference with vegetation cover on nearby low ground during the late Holocene, there is no evidence that this triggered or affected the accumulation of windblown sediment on the plateau.
5. Radiocarbon dating implies that over much of the plateau, rates of sediment accumulation averaged 0·1–0·2 mm a^{-1}, but reached *c*. 0·6 mm a^{-1} in the area of the thickest deposits. If adjacent cliff faces formed the sole source of sediment, an average rockwall retreat rate of 0·06–0·07 mm a^{-1} is implied, equivalent to the removal of 420–480 mm of rock (averaged over the face) during the mid- to late Holocene. This suggests that small-scale granular disaggregation and release of fine gravel may predominate over rockfall as an agent of cliff recession under present conditions.
6. The origin of the Storr deposits suggests that plateau-top aeolian sediments on other Scottish mountains may originally have accumulated in a similar manner, but have subsequently been eroded and redeposited on lee slopes following breakage of the vegetation mat. The causes of vegetation disruption remain uncertain.

ACKNOWLEDGEMENTS

The fieldwork for this research was supported by a grant from the British Geomorphological Research Group, and the radiocarbon analyses were supported by the NERC Radiocarbon Laboratory, East Kilbride, Scotland. The author thanks Peter Taylor, Lachan Renwick, Graeme Gordon and Georgina Hallam for field assistance, Dr

Douglas Harkness for making available funds to cover AMS beam time, Colin Cameron for laboratory assistance, Lois Wood for the pollen analyses, Professor Graeme Whittington for helpful discussion of the pollen analyses, Graeme Sandeman for preparing the figures, and Dr Peter Wilson for his comments on the original manuscript.

REFERENCES

Anderson, F. W. and Dunham, K. W. 1996. *The Geology of Northern Skye*, Memoirs of the Geological Survey of the United Kingdom, HMSO, Edinburgh.

Ball, D. F. and Goodier, R. 1974. 'Ronas Hill, Shetland: a preliminary account of its ground pattern features resulting from the action of frost and wind', in Goodier, R. (Ed.), *The Natural Environment of Shetland*, Natural Conservancy Council, Edinburgh, 89–106.

Ballantyne, C. K. 1987. 'The present-day periglaciation of upland Britain', in Boardman, J. (Ed.), *Periglacial Processes and Landforms in Britain and Ireland*, Cambridge University Press, Cambridge, 113–126.

Ballantyne, C. K. 1990. 'The Late Quaternary glacial history of the Trotternish Escarpment, Isle of Skye, Scotland, and its implications for ice-sheet reconstruction', *Proceedings of the Geologists' Association*, **101**, 171–186.

Ballantyne, C. K. 1991a, 'Holocene geomorphic activity in the Scottish Highlands', *Scottish Geographical Magazine*, **107**, 84–98.

Ballantyne, C. K. 1991b. 'Late Holocene erosion in upland Britain: climatic deterioration or human influence?', *The Holocene*, **1**, 81–85.

Ballantyne, C. K. 1991c. 'Periglacial features on the mountains of Skye', in Ballantyne, C. K., Benn, D. I., Lowe, J. J. and Walker, M. J. C. (Eds), *The Quaternary of the Isle of Skye: Field Guide*, Quaternary Research Association, Cambridge, 68–81.

Ballantyne, C. K. 1991d. 'The landslides of Skye', in Ballantyne, C. K., Benn, D. I., Lowe, J. J. and Walker, M. J. C. (Eds), *The Quaternary of the Isle of Skye: Field Guide*, Quaternary Research Association, Cambridge, 82–89.

Ballantyne, C. K. 1991e. 'The landslides of Trotternish, Isle of Skye', *Scottish Geographical Magazine*, **107**, 130–135.

Ballantyne, C. K. 1993. 'An Teallach', in Gordon, J. E. and Sutherland, D. G. (Eds), *Quaternary of Scotland*, Chapman and Hall, London, 110–115.

Ballantyne, C. K. 1994. 'Gibbsitic soils on former nunataks: implications for ice-sheet reconstruction', *Journal of Quaternary Science*, **9**, 73–80.

Ballantyne, C. K. 1995. 'Periglacial features on the mountains of Assynt and Coigach', in Lawson, T. J. (Ed.), *The Quaternary of Assynt and Coigach: Field Guide*, Quaternary Research Association, Cambridge, 47–60.

Ballantyne, C. K. and Eckford, J. D. 1984. 'Characteristics and evolution of two relict talus slopes in Scotland', *Scottish Geographical Magazine*, **100**, 20–33.

Ballantyne, C. K. and Harris, C. 1994. *The Periglaciation of Great Britain*, Cambridge University Press, Cambridge, 330 pp.

Ballantyne, C. K. and Whittington, G. W. 1987. 'Niveo-aeolian sand deposits on An Teallach, Wester Ross, Scotland', *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **78**, 51–63.

Ballantyne, C. K., Stone, J. O. and Fifield, L. K. 1998. 'Cosmogenic Cl-36 dating of postglacial landsliding at The Storr, Isle of Skye, Scotland', *The Holocene*, in press.

Birks, H. J. B. 1973. *Past and Present Vegetation of the Isle of Skye: a Palaeoecological Study*, Cambridge University Press, Cambridge, 415 pp.

Birks, H. J. B. and Williams, W. 1983. 'Late Quaternary vegetational history of the Inner Hebrides', *Proceedings of the Royal Society of Edinburgh*, **83**, 269–292.

Birse, E. L. 1980. 'Suggested amendments to the world soil classification to accommodate Scottish aeolian and mountain soils', *Journal of Soil Science*, **31**, 117–124.

Bowen, A. J. and Lindley, D. 1977. 'A wind-tunnel investigation of the wind speed and turbulence characteristics close to the ground over various escarpment shapes', *Boundary Layer Meteorology*, **12**, 259–271.

Cui, B., Komar, P. and Baba, J. 1983. 'Settling velocities of natural sand grains in air', *Journal of Sedimentary Petrology*, **53**, 1205–1211.

Francou, B., Federmayer, L., Kuang-Yi, L. and Yaning, C. 1990. *Explorations géomorphologiques dans l'ouest des Kun Lun (Xinjiang, Chine)*, Centre de Géomorphologie de Caen, CNRS, France, Rapports scientifiques et techniques, **5**, 91 pp.

French, H. M. 1996. *The Periglacial Environment*, 2nd edn, Longman, Harlow, 341 pp.

Godard, A. 1965. *Recherches de Géomorphologie en Écosse du Nord-Ouest*, Masson, Paris, 603 pp.

Good, T. R. and Bryant, I. D. 1985. 'Fluvio-aeolian sedimentation – an example from Banks Island, NWT, Canada', *Geografiska Annaler*, **67A**, 33–46.

Goodier, R. and Ball, D. F. 1975. 'Ward Hill, Orkney: patterned ground features and their origins', in Goodier, R. (Ed.), *The Natural Environment of Orkney*, Nature Conservancy Council, Edinburgh, 47–56.

Hétu, B. 1992. 'Coarse cliff-top sedimentation in northern Gaspésie, Québec (Canada)', *Earth Surface Processes and Landforms*, **17**, 95–108.

Hinchliffe, S., Ballantyne, C. K. and Walden, J. 1998. 'The structure and sedimentology of relict talus, Trotternish, northern Skye, Scotland', *Earth Surface Processes and Landforms*, in press.

Koster, E. A. 1988. 'Ancient and modern cold-climate aeolian sand deposition: a review', *Journal of Quaternary Science*, **3**, 69–83.

Lowe, J. J. and Walker, M. J. C. 1991. 'Vegetational history of the Isle of Skye: II. The Flandrian', in Ballantyne, C. K., Benn, D. I., Lowe, J. J. and Walker, M. J. C. (Eds), *The Quaternary of the Isle of Skye: Field Guide*, Quaternary Research Association, Cambridge, 119–142.

Marsh, W. M. and Marsh, B. D. 1987. 'Wind erosion and sand dune formation on high Lake Superior bluffs', *Geograkiska Annaler*, **69A**, 379–391.

McKenna-Neuman, C. and Gilbert, R. 1986. 'Aeolian processes and landforms of glaciofluvial environments of southeastern Baffin Island, N.W.T., Canada', in Nickling, W. G. (Ed.), *Aeolian Geomorphology*, Allen and Unwin, Boston, 213–235.

McManus, J. 1988. 'Grain size determination and interpretation', in Tucker, M. (Ed.), *Techniques in Sedimentology*, Blackwell, Oxford, 63–85.

Meteorological Office 1977. *Average Annual Rainfall: Northern Britain*, Meteorological Office, Bracknell.
Nickling, W. G. 1978. 'Eolian sediment transport during dust storms: Slims River valley, Yukon Territory', *Canadian Journal of Earth Sciences*, **15**, 1069–1084.
Peach, B. N., Horne, J., Gunn, W., Clough, C. T., Hinxman, L. T., Cadell, H. M., Greenly, E., Pocock, T. I. and Crampton, C. B. 1913. *The Geology of the Fannich Mountains and the Country around Upper Loch Maree and Strath Broom*, Memoirs of the Geological Survey, Scotland, Edinburgh, 127 pp.
Péwé, T. L. 1975. *Quaternary Geology of Alaska*, United States Geological Survey, Professional Paper, **835**, 145 pp.
Pissart, A., Vincent, J. S. and Edlund, S. A. 1977. 'Dépôts et phénomènes éoliens sur l'île de Banks, Territoires do Nord-Quest, Canada', *Canadian Journal of Earth Sciences*, **14**, 2452–2480.
Pye, K. and Paine, A. D. M. 1983. 'Nature and source of aeolian deposits near the summit of Ben Arkle, Northwest Scotland', *Geologie en Mijnbouw*, **68**, 13–18.
Pye, K. and Tsoar, H. 1990. *Aeolian Sand and Sand Dunes*, Unwin Hyman, London, 396 pp.
Riezebos, P. A., Boulton, G. S., van der Meer, J. J. M., Ruegg, G. H. J., Beets, D. J., Castel, I. I. Y., Hart, J., Quinn, I., Thornton, M. and van der Wateren, F. M. 1986. 'Products and effects of modern eolian activity on a nineteenth-century glacier-pushed ridge in West Spitsbergen, Svalbard', *Arctic and Alpine Research*, **18**, 389–396.
Salt, K. E. and Ballantyne, C. K. 1997. 'The structure and sedimentology of relict talus, Knockan, Assynt, N.W. Scotland', *Scottish Geographical Magazine*, **113**, 82–89.
Stuiver, M. and Becker, B. 1993. 'High precision calibration of the radiocarbon time scale AD 1950–6000 BC', *Radiocarbon*, **35**, 35–65.
Stuiver, M. and Reimer, P. J. 1993. 'Extended 14C database and revised CALIB radiocarbon calibration program', *Radiocarbon*, **35**, 215–230.
Thorn, C. E. and Darmody, R. G. 1980. 'Contemporary eolian sediments in the alpine zone, Colorado Front Range', *Physical Geography*, **1**, 162–171.
Thorn, C. E. and Darmody, R. G. 1985. 'Grain-size distribution of the insoluble component of contemporary eolian deposits in the Alpine zone, Front Range, Colorado', *Arctic and Alpine Research*, **17**, 433–442.
Tipping, R. 1995. 'Holocene landscape change at Carn Dubh, near Pitlochry, Perthshire, Scotland', *Journal of Quaternary Science*, **10**, 59–75.
Vasari, Y. and Vasari, A. 1968. 'Late- and Post-glacial macrophytic vegetation in the lochs of northern Scotland', *Acta Botanica Fennica*, **80**, 1–20.
Wilson, P. 1989. 'Nature, origin and age of Holocene aeolian sand on Muckish Mountain, Co. Donegal, Ireland', *Boreas*, **18**, 159–168.

